

(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization  
International Bureau



(43) International Publication Date  
20 February 2003 (20.02.2003)

PCT

(10) International Publication Number  
**WO 03/014789 A2**

(51) International Patent Classification<sup>7</sup>: **G02B 6/35**

(21) International Application Number: **PCT/IB02/02117**

(22) International Filing Date: **7 June 2002 (07.06.2002)**

(25) Filing Language: **English**

(26) Publication Language: **English**

(30) Priority Data:  
01810658.3 **5 July 2001 (05.07.2001) EP**

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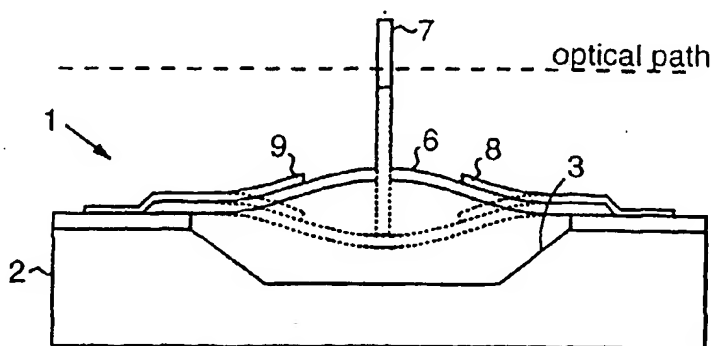
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(81) Designated States (national): AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NO, NZ, OM, PI, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VN, YU, ZA, ZM, ZW.

(84) Designated States (regional): ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM),

[Continued on next page]

(54) Title: **MICROSYSTEM SWITCHES**



(57) Abstract: A microsystem switch (1, 20, 25, 30, 33) has a support (2) defining a recess (3), and a flexible bridge (6) is mounted on the support (2) bridging the recess (3). The bridge (6) is shaped so as to hold selectively a concave support stable state, in which the bridge bulges out of the recess (3). The switch includes an actuator (8, 9; 26, 27) for effecting flexing of the bridge (6) between the stable states, and a switching element (7, 31, 34) is mounted on the bridge (6) such that movement of the bridge between the stable states moves the switching element

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between an on position and an off position. According to another design, a microsystem switch (40, 55) has a support (41) defining a recess (42), and an elongate torsion member (44) is mounted on the support (41) bridging the recess (42). A flexible bridge (43, 56) is mounted on the support (41) bridging the recess (42) in a direction substantially perpendicular to the torsion member (44). The bridge (43, 56) is connected to the torsion member (44) at the cross-point thereof so that a first section of the bridge extends between the cross-point and one side of the recess (42) and a second section of the bridge extends between the cross-point and the opposite side of the recess (42). The bridge (43, 56) is shaped so as to hold selectively a first stable state, in which the first section of the bridge bulges into the recess and the second section of the bridge bulges out of the recess, and a second stable state in which this configuration is reversed. A switching element (45) is mounted at the cross-point of the bridge (43, 56) and torsion member (44), and an actuator (46a, 46b; 58a, 58b) is again provided for effecting flexing of the bridge (43, 56) between the stable states. Here, movement of the bridge (43, 56) between the stable states effects twisting of the torsion member (44) and rotation of the switching element (45) between an on position and an off position. Switching devices incorporating these switches, and switching apparatus comprising arrays of such switching devices, are also provided.



European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, IJ, MC, NL, PT, SE, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

*For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.*

**Published:**

- *without international search report and to be republished upon receipt of that report*

## MICROSYSTEM SWITCHES

This invention relates generally to microsystem switches.

Microsystem switches, such as MEMS (Micro-Electro-Mechanical System) switches,  
5 are microfabricated devices which provide for high levels of integration. Various examples of  
microsystem switches are known. For example, International Patent Application No. WO  
00/25160 discloses various optical MEMS switches for use in optical switching arrays. Here,  
optical waveguides are arranged in a grid with fluid-filled trenches formed at the cross-points  
of each pair of waveguides. The switches utilise MEMS mirrors which slide in the trenches  
10 between on positions, in which a mirror reflects light from an input waveguide into an output  
waveguide, and off positions in which a mirror is withdrawn from the optical path and light  
continues to propagate along the input waveguide. The switches may be formed on the same  
chip as the waveguide array or on a different chip which is flip-chip mounted with the  
waveguide array chip. In some embodiments of the switch the mirror actuator serves to slide  
15 the mirror in the plane of the chip. In another embodiment the mirror is mounted on a plate  
and activation of an electrostatic actuator causes flexing of the plate to lift the mirror into the  
off position in an out-of-plane direction.

A key problem with existing switch designs of the type described above is that power  
must be applied continuously to hold the switch in one of its two operating positions. An  
20 efficient microsystem switch design, particularly in the context of switching arrays, should  
have a simple construction for ease of fabrication, and offer low power consumption. A paper  
entitled "A Unique Latching 2x2 MEMS Fibre Optics Switch", Hichwa et al, OMEMS 2000,  
21 August 2000, discloses a bistable optical switch with a complex electrostatic mirror  
actuation system, fabricated in the space between two crossed waveguides, for sliding the  
25 mirror in the plane of the substrate into the cross-point of the waveguides. The actuation  
system employs a set of comb drives and two flexible hinges for latching the device in its  
stable states. A flip-chip bonded 4x4 array design based on this switch is discussed in "4x4  
Matrix Switch Based on MEMS Switches and Integrated Waveguides", Dellman et al,  
pp1332-1335, Transducer '01, Eurosensors XV, the 11th International Conference on  
30 Solid-State Sensors and Actuators, June 10-14, 2001, Digest of Technical Papers, Volume 2,  
published by Springer. While this switch offers bistable operation, the size and complexity of  
the switching mechanism prejudices the objectives of an efficient array design.

According to one aspect of the present invention there is provided a microsystem switch comprising:

a support defining a recess;

a flexible bridge mounted on the support and bridging the recess, the bridge being  
5 shaped so as to hold selectively a concave stable state, in which the bridge bulges into the recess, and a convex stable state in which the bridge bulges out of the recess;

an actuator for effecting flexing of the bridge out of each of the stable states into the other of the stable states; and

a switching element mounted on the bridge such that movement of the bridge between  
10 the stable states moves the switching element between an on position and an off position.

In embodiments of the invention therefore, switching is achieved by effecting flexing of the bistable bridge between its concave and convex stable states, thus moving the switching element into and out of the recess between its on and off positions. Embodiments of the invention thus offer a bistable switch with elegantly simple construction and operation as well  
15 as low power requirements. Switches embodying the invention are small to realise and easy to fabricate, allowing realisation of highly efficient switching arrays.

The flexible bridge can be shaped for bistable operation by preforming and/or prestressing the bridge, though preferably the bridge is prestressed whether or not it is preformed with a generally convex/concave shape. In this regard, it will be understood by  
20 those skilled in the art that fabrication processes to achieve a preformed shape can result, by their nature, in a certain degree of prestressing, so that the resulting structure is subject to some degree of stress in situ.

While embodiments can be envisaged where the bridge is formed in more than one section, for example one section on each side of the switching element, for simplicity of  
25 construction and fabrication the bridge preferably comprises a simple, flexible membrane. Moreover, the recess is preferably formed in a substantially flat surface of the support, the bridge being mounted on this surface so as to extend over the recess. Arrangements can of course be envisaged where the recess is defined by a raised structure of the support, and such a raised structure might be formed by extensions of the bridge, the point being that the recess,  
30 however defined, provides a space for the movement of the bridge. The former arrangement is preferred, however, as providing a particularly simple and compact design.

Various actuator mechanisms might be employed to effect flexing of the bridge between its stable states. The actuator could be arranged to impart an impulse to the bridge to toggle the switch between states. For example, embodiments can be envisaged where the actuator generates a surface acoustic wave to impart the toggling impulse. Various other possible actuator mechanisms will be discussed hereinafter. In preferred embodiments, however, the actuator comprises a pair of bimorph actuation layers, each bimorph actuation layer extending over a respective portion of the bridge so as to form therewith a bimorph structure. On activation of one of these layers, differential expansion in the corresponding bimorph structure exerts a force causing flexing of the bridge out of one stable state into the other stable state. The layers are arranged such that activation of one layer causes flexing of the bridge out of the convex stable state into the concave stable state, and activation of the other layer causes flexing of the bridge out of the concave stable state into the convex stable state. Various bimorph structures can be envisaged here, and the nature of the bimorph activation layers can vary accordingly. By way of example, embodiments can be envisaged where the bimorph actuation layers are formed of a porous material which swells when activated, by exposing the layer to humidity or some other appropriate activating agent, to produce the differential expansion in the bimorph structure. In particularly preferred embodiments however, each bimorph actuation layer comprise a heater which has a thermal expansion coefficient different to that of the portion of the bridge it overlays, whereby heating of the heater causes the differential expansion in the bimorph. This provides a particularly simple and efficient actuation mechanism exploiting bimorph forces to toggle the switch between states. Embodiments might be envisaged where the heaters are disposed on opposite surfaces of the bridge on the same side of the switching element. However, to avoid potential problems of heat conduction between the heaters through the thickness of the bridge, it is preferred that the heaters are disposed on opposite sides of the switching element. In some embodiments, the heaters are disposed on opposite surfaces of the bridge and on opposite sides of the switching element. Here the heaters can conveniently be made of the same material. In other embodiments, to simplify the fabrication process, the heaters are disposed on the same surface of the bridge on opposite sides of the switching element. Here, the thermal expansion coefficient of one heater should be greater than that of the portion of the bridge it overlays, and the thermal expansion coefficient of the other heater should be less than that of the portion of the bridge it overlays. Preferred embodiments employing such

heaters with a flexible membrane bridge will be illustrated hereinafter. While embodiments might be envisaged where the heaters are activated optically for example, in the preferred embodiments described below the heaters are activated electrically.

If desired, to reduce the force required to effect switching, the bridge may be formed  
5 with a spring structure on each side of the switching element in a direction along the extent of the bridge. Such a spring structure may comprise, for example, lateral and/or central cut-away portions to facilitate flexing of the bridge between its stable states

In the preferred embodiments of this aspect of the invention detailed below the bridge has a substantially symmetrical curved profile in cross section along its extent across the  
10 recess, and the switching element is mounted substantially mid-way along the bridge. In these embodiments, the switching element is mounted on the side of the bridge remote from the recess. This allows convenient implementation of a flip-chip mounted switch arrangement as discussed further below. The switching element itself can vary according to the type of switch in which it is employed. In an electrical switch, for example, the switching element may be an  
15 electrical contact. In an optical switch, the switching element comprises an optical element. While the optical element could be a shutter, lens, grating or other element for switching a light beam, in the preferred embodiments the optical element comprises a mirror.

In switches embodying the first aspect of the invention described above, the switching element is translated between its on and off positions as the bridge switches between its stable  
20 states. In accordance with a second aspect of the invention there is provided a microsystem switch comprising:

- a support defining a recess;

- an elongate torsion member mounted on the support and bridging the recess;

- a flexible bridge mounted on the support and bridging the recess in a direction

25 substantially perpendicular to the torsion member, the bridge being connected to the torsion member at the cross-point thereof so that a first section of the bridge extends between the cross-point and one side of the recess and a second section of the bridge extends between the cross-point and the opposite side of the recess, wherein the bridge is shaped so as to hold selectively a first stable state, in which the first section of the bridge bulges into the recess and  
30 the second section of the bridge bulges out of the recess, and a second stable state in which the first section of the bridge bulges out of the recess and the second section of the bridge bulges into the recess;

an actuator for effecting flexing of the bridge out of each of the stable states into the other of the stable states; and

a switching element mounted at the cross-point of the bridge and torsion member;

wherein movement of the bridge between the stable states effects twisting of the  
5 torsion member and rotation of the switching element between an on position and an off position.

Embodiments of this aspect of the invention therefore employ similar principles to embodiments of the first aspect of the invention, but the switching element describes a rotational movement between the on and off positions. This is achieved by provision of the  
10 torsion member which is arranged as described above effectively to partition the bridge into two sections, the bridge being shaped to hold one stable state in which one section bulges into, and the other section bulges out of, the recess, and another stable state in which this configuration is reversed. The switching element is mounted at the cross-point of the bridge and torsion member so that, as the bridge moves between its stable states, the switching  
15 element undergoes a rotation stabilised by the torsion member which twists during this movement. Embodiments of this aspect of the invention thus provide the advantages of simple construction and operation, with low power requirements, small realisation and ease of fabrication as with embodiments discussed above, and additionally provide a more controlled, rotational movement of the switching element. This provides for particularly advantageous  
20 switch designs as discussed further below.

While other arrangements might be envisaged, in preferred arrangements the cross-point is located substantially mid-way along the extent of each of the bridge and torsion member across the recess. Other preferred and optional features described in relation to embodiments of the first aspect of the invention apply equally here where appropriate. For  
25 example, the bridge preferably comprises a flexible membrane, and the switching element is preferably mounted on the side of the bridge remote from the recess. The actuator preferably comprises a pair of bimorph actuation layers, most preferably heaters, each extending over a section of the bridge whereby flexing of the bridge is effected by bimorph forces as described above. In addition, while the torsion member could be formed in more than one section, in  
30 preferred embodiments the torsion member comprises a simple torsion bar. Further, where the switching element comprises a substantially planar element (as in the preferred optical switch embodiments where the switching element comprises a mirror), the switching element is

preferably mounted so as to rotate substantially in its own plane between the on and off positions.

The invention also provides switching apparatus comprising an array of switches as described above in relation to the first or the second aspect of the invention. The invention  
5 further provides an optical switching device comprising: a switch as described above having an optical switching element; and a waveguide structure having an optical waveguide and defining a cavity intersecting the waveguide; wherein the switch is disposed relative to the waveguide structure such that movement of the bridge between the stable states moves the optical element in the cavity between the on position, in which the optical element intersects  
10 the optical path defined by the waveguide, and the off position in which the optical element does not intersect the optical path. A still further aspect of the invention provides optical switching apparatus comprising an array of such optical switching devices. In such switching apparatus, the waveguide structures of the devices are preferably integrated in a waveguide array chip, and the switches of the devices are preferably integrated in a switch array chip,  
15 providing a convenient flip-chip mounted arrangement.

Preferred embodiments of the invention will now be described, by way of example, with reference to the accompanying drawings in which:

- Figure 1 illustrates an optical switch embodying the first aspect of the invention;
- Figure 2 shows the two stable states of the switch of Figure 1;
- 20 Figures 3a to 3c illustrate successive stages in switching of the Figure 1 switch;
- Figure 4 illustrates a switching device incorporating the switch of Figure 1;
- Figure 5 illustrates a modified version of the switch of Figure 1;
- Figure 6 shows another example of an optical switch embodying the first aspect of the invention;
- 25 Figure 7 illustrates one example of an electrical switch embodying the first aspect of the invention;
- Figure 8 illustrates another example of an electrical switch embodying the first aspect of the invention;
- Figure 9 illustrates an optical switch embodying the second aspect of the invention;
- 30 Figure 10 illustrates an unstable state of the Figure 9 switch;
- Figures 11a and 11b show the two stable states of the Figure 9 switch;



Figure 12 illustrates optical switching apparatus incorporating an array of optical switches as shown in Figure 9; and

Figures 13 and 14 illustrate another example of an optical switch embodying the second aspect of the invention.

5        Figures 1 to 3c show schematic side views of one embodiment of a MEMS switch 1. Referring to Figure 1, the switch 1 includes a support 2 having a recess 3 in the surface thereof. The support 2 here is formed by a substrate 4 and a surface layer 5 resulting from the fabrication process for formation of the recess 3. The switch 1 also includes a bridge structure in the form of flexible membrane 6 which is mounted on the surface of support 2 so as to  
10    bridge the recess 3. The bridge membrane 6 has a symmetrical curved profile as illustrated in the figure. This shape is achieved in this embodiment by a fabrication process which results in the membrane being under compressive stress, so that the membrane buckles and bulges out of the recess into the curved shape shown. Various fabrication processes can be employed to achieve this prestressing of the membrane as will be apparent to those skilled in the art. For  
15    example, a membrane formed by a layer of silicon can be oxidised to impose a force which tends to cause elongation of the membrane. The membrane will thus be under compressive stress while still attached to the wafer, and when the membrane is released (by etching of the recess) the membrane will "expand" and buckle to achieve the shape shown in the figure. The membrane could also be deposited with a certain degree of compressive stress, for example by  
20    a chemical vapour deposition or plasma enhanced chemical vapour deposition process as will be apparent to those skilled in the art. As a further example, the membrane could be formed as a flat layer and a mechanism employed subsequently to push one (or each) end of the membrane towards the other, thus compressing the membrane and forcing it to buckle into the shape illustrated.

25        The resulting membrane 6 constitutes a bistable structure, having a generally convex stable state as shown in Figure 1 where the membrane bulges out of the recess 3, and a generally concave stable state in which the membrane bulges into the recess 3. A switching element in the form of mirror 7 is mounted mid-way along membrane 6 on the side remote from the recess. The plane of the mirror extends generally perpendicular to the longitudinal  
30    extent of the membrane. The switch 1 also includes an actuator for effecting flexing of the membrane 6 between its stable states. In this embodiment the membrane is formed of a dielectric material, and the actuator comprises a pair of resistive heaters 8, 9 formed by

conductive layers extending over the upper surface of the membrane, on either side of mirror 7, as illustrated. One heater is a pull-down heater 8 and is formed of a material having a thermal expansion coefficient  $\alpha_d$  which is greater than the thermal expansion coefficient  $\alpha_m$  of the membrane 6. The other heater is a pull-up heater 9, and the material of this heater has a thermal expansion coefficient  $\alpha_u$  which is less than  $\alpha_m$ .

In operation, when the switch is in the convex state of Figure 1, application of a current to heat the pull-down heater 8 results in a downwardly-directed bimorph force which effects flexing of membrane 6 out of its convex stable state into its concave stable state as shown by the broken lines in Figure 2. In this state, application of a current to heat the pull-up heater 9 results in an upwardly directed bimorph force effecting flexing of the membrane out of the concave state back into the convex state. This movement of the membrane 6 between its stable states results in movement of mirror 7 between an on position (convex state) for intersecting an optical path as indicated in Figure 2, and an off position (concave state) wherein the mirror does not intersect the optical path. Figures 3a to 3c show the configuration of the switch 1 at successive stages in the switching process, Figure 3a showing the convex stable state, Figure 3c showing the concave stable state, and Figure 3b showing the (unstable) intermediate state wherein the membrane has a generally S-shaped configuration.

Figure 4 shows the switch 1 incorporated in an optical switching device embodying the invention. The device is partially cut-away in this schematic view to illustrate the arrangement more clearly. The device includes a waveguide structure 10 having a pair of crossed waveguides 11 and 12. While other configurations are possible, in this particular example the waveguides 11, 12 are arranged along orthogonal X and Y axes. A cavity 13 is provided in structure 10 at the cross-point of the waveguides 11 and 12. Switch 1 is arranged relative to waveguide structure 10 so that the mirror 7 moves in the cavity 13 between its on and off positions. In the on position, the mirror intersects both the X and Y optical paths, with the plane of the mirror at 45° to each, so that light incident on the mirror from one waveguide is reflected into the other waveguide. In the off position, the mirror is withdrawn from the optical paths so that light propagates across the cavity and continues in the same waveguide. Cavity 13 is ideally filled with index-matching fluid to inhibit cross-connection optical losses.

The form of heaters 8 and 9 can be seen more clearly in this figure, the electrical connections for supplying current to these heaters being indicated at 18 and 19 respectively. The switch 1 and waveguide structure 10 are self-aligned by means of mesas 15 (only one of

which is shown in the figure) on support 2 which engage in recesses 16 of the waveguide structure. While a single switching device is shown here, in practice the device will generally be one of multiple such devices provided in an optical switching array. In such an array, the waveguide structure 10 is provided by a waveguide array chip in which multiple waveguides are arranged in a grid. Similarly, the switches 1 are provided on a switching array chip which is flip-chip mounted with the waveguide chip so that one switch operates at the cross-point of each pair of waveguides.

As most clearly seen in Figure 1, in this embodiment the heaters 8, 9 extend along the membrane 6 over the steepest portion of the curved membrane profile on each side of the mirror. In these regions the bimorph effect operates to greatest effect in inducing flexing of the membrane. If desired, however, the membrane can be formed with a spring structure to further assist the switching process. Figure 5 shows a plan view of a switch 20 incorporating this modification. The switch 20 is generally similar to switch 1 and like parts are labelled accordingly. In this embodiment, however, the membrane 6 is formed with a spring structure, indicated generally at 21, on either side of the mirror 7. Each spring structure 21 is formed by a pair of lateral cut-away portions 22a and 22b, and a central cut-away portion 23. These spring structures 21 provide a degree of longitudinal compliance in the bridge membrane, so that the energy needed to reach the toggling point of the membrane is reduced. While providing a degree of compliance, however, the spring structures 21 should be stiff enough so that vibration or shocks to which the switch may be subjected in use do not produce enough force to toggle the membrane. A trade-off therefore exists between these two considerations.

Figure 6 shows a schematic side view of another embodiment of an optical switch. The switch 25 of this embodiment is generally similar to the switch 1 of Figure 1, and only the differences will be described here. As illustrated in the figure, the heaters 26, 27 here are provided on opposite surfaces of the membrane bridge. This configuration allows the heaters 26, 27 to be made of the same material. The thermal expansion coefficient of this material can be either greater than or less than that of the membrane, the choice here determining which of the upper- and lower-surface heaters serves as the pull-down heater, and which serves as the pull-up heater.

The switch designs described above can also be employed for electrical switches. Figures 7 and 8 show two examples where the design corresponds generally to that of Figure 1, but the mirror 7 is replaced by an electrical contact. In the switch 30 of Figure 7, a bridging

contact 31 is mounted on the membrane so as to extend substantially perpendicular to the longitudinal extent of the membrane. The bridging contact 31 extends laterally beyond the sides of the membrane so that, when the membrane is in the concave stable state, the contact 31 connects with electrical contacts 32a and 32b on the support. The concave state here thus corresponds to the on position of the switch. In the switch 33 of Figure 8, a bridging contact 34 is mounted on a spacer 35 on the membrane. This contact is arranged to connect with electrical contacts provided on a facing structure (not shown), such as a contact array chip with electrical contacts for an array of switches 33. Here, therefore, the convex stable state corresponds to the on position of the switch. In both embodiments, the bridging contact 31, 34 should be sufficiently mechanically compliant to accommodate fabrication tolerances and provide a suitable contact pressure.

Figure 9 is a schematic plan view of a MEMS switch 40 embodying the second aspect of the invention. The switch 40 includes a support 41, having a recess 42 in the surface thereof, and a bridge in the form of flexible membrane 43 which extends across the recess 42. The switch further includes a torsion member in the form of bar 44 which bridges the recess in a direction substantially perpendicular to the membrane 43. Torsion bar 44 can be made of any suitable material which provides for the torsional movement of the bar described below. The torsion bar 44 and bridge membrane 43 are connected together at the cross-point thereof, and a mirror 45 is mounted at the cross-point on the side remote from the recess 42. The plane of mirror 45 extends substantially parallel to the longitudinal extent of the membrane 43. The membrane 43 is formed of a dielectric material, and the switch actuator again comprises a pair of resistive heaters 46a, 46b extending over the upper surface of the membrane on either side of the cross-point. The heaters 46a, 46b are formed as layers of the same conductive material, this material having a thermal expansion coefficient  $\alpha_h$  which is different to the thermal expansion coefficient  $\alpha_m$  of the membrane material.

As with the earlier embodiments, the membrane 43 is shaped so as to hold selectively one of two stable states. In this embodiment, however, the configuration of the membrane is somewhat different. Figure 10 illustrates the overall symmetry of the design, where it is to be understood that the shape shown in this figure is mechanically unstable. In the form illustrated, the two sections of the membrane 43 extending between the torsion bar 44 and respective sides of the recess 42 have a convex, curved profile. In this unstable state the membrane is under compressive stress so that, when released, the membrane adopts one of

two stable states having a generally S-shaped configuration. One stable state is shown in Figure 11a, where the right-hand section of the membrane bulges into recess 42, and the left-hand section of the membrane bulges out of recess 42. Figure 11b shows the other stable state where the right-hand section of the membrane bulges out of, and the left-hand section bulges into, the recess 42. Various fabrication processes, such as those described above in relation to the first embodiment, can be employed to achieve the membrane shape of this embodiment as will be apparent to those skilled in the art. In Figures 10 to 11b, the two surface layers shown on top of the substrate of support 41 result from the fabrication steps for torsion bar 44 in this example, though clearly these layers are not necessary for operation of the device and may not be present in other embodiments..

    Toggling of the membrane between its stable states is achieved as before by application of power to heaters 46a, 46b. Which of the heaters is activated to cause toggling out of a given state depends on whether  $\alpha_h$  is greater or less than  $\alpha_m$ . Assuming here that  $\alpha_h$  is less than  $\alpha_m$ , then the heater on the "high side" is activated to effect switching. Thus, when heater 46b is activated in the state shown in Figure 11a, the differential expansion results in a downwardly-directed bimorph force on this side, causing flexing of the membrane into the state shown in Figure 11b. Similarly, activation of heater 46a in Figure 11b effects flexing of the membrane back into the state shown in Figure 11a. It can be seen from these figures that movement of membrane 43 between its stable states effects twisting of torsion bar 44 and rotation of the mirror 45 in its own plane. In use, one of the mirror positions constitutes an on position, where the mirror intersects an optical path to reflect the incident light beam, and the other mirror position constitutes an off position where the mirror is retracted from the optical path and the light beam continues to propagate along the path.

    The design of switch 40 provides a number of advantages over the switch designs of the earlier embodiments. It can be seen from Figures 3a to 3c that, with the earlier designs where the mirror undergoes translational movement between its on and off positions, the mirror tends to wobble out of its own plane during switching due to the asymmetry of the switching action. With switch 40, however, the rotational movement of mirror 45, stabilised by the torsional movement of torsion bar 44, is highly controlled, and the mirror rotates in its own plane. The design is thus mechanically less compliant to out-of-plane wobble, allowing movement of the mirror in a cavity formed as a narrow trench intersecting a waveguide. With the former design, the mirror would need to be guided to allow movement into a narrow

trench. In addition, as mirror 45 moves in a fluid-filled cavity in the waveguide structure, the rotational movement constitutes a sheer action which presents less disturbance to the fluid than the mirror movement in the earlier designs. Further, the design of switch 40 allows the heaters 46a, 46b to be formed of the same metal applied to the same surface of the membrane

5 43. With the earlier design, heaters formed on the same surface of the membrane must be formed of different materials.

Figure 12 shows a schematic, partially cut-away plan view of switching apparatus comprising an integrated array of optical switching devices utilising switch 40. A waveguide array chip 50 provides a mesh or grid of waveguides 51. In this particular example, the

10 waveguides are arranged in an orthogonal grid. At the cross-point of each pair of waveguides 51, a cavity is formed as a narrow, deep-etched trench 52 orientated as shown. A flip-chip mounted switching array chip 53 provides an array of switches 40 arranged so that the mirrors 45 of the switches project downwardly into trenches 52, one at each of the waveguide cross-points, with the plane of each mirror aligned with the longitudinal extent of the

15 corresponding trench. The mirror of each switch can thus be rotated in the trench between the on position, in which the mirror reflects light propagating along one waveguide into the orthogonal waveguide, and the off position in which the mirror is withdrawn from the optical path and light continues to propagate along the input waveguide.

Figures 13 and 14 are schematic plan and side views respectively of another

20 embodiment of a MEMS switch. The switch 55 of this embodiment is of similar design to switch 40, and only the key differences will be discussed here. An electrostatic actuation mechanism is employed for switch 55, and in this embodiment the bridge membrane 56 is formed with laterally enlarged portions 57a, 57b on either side of the cross-point with the torsion bar. A metal layer is applied on each side of the cross-point forming pads 58a, 58b on

25 portions 57a, 57b respectively. The substrate 59 here is also formed of conductive material, and the switching action is effected by application of a voltage between the substrate and the conductive pad on the "high side" of the bridge membrane. This is illustrated in Figure 14 where, in the state shown, the right-hand section of the membrane is the high side and the voltage is thus applied between pad 58a and substrate 59. The resulting force of attraction

30 between pad 58a and substrate 59 pulls the high side down and thus effects flexing of the membrane into its other stable state. Switching back to the initial state is then effected by applying a voltage between pad 58b and the substrate.

It will be seen that the above embodiments provide highly efficient microsystem switch designs with simple, robust construction and operation as well as low power requirements, power being required only to effect switching between the two stable states. The designs offer ease of fabrication and small-scale realisation, allowing the construction of highly efficient switching arrays. It will be appreciated, however, that while particularly preferred embodiments have been described in detail above, many changes and modifications can be made to these embodiments. By way of example, while the thermal bimorph actuation systems described above are preferred as a particularly simple and effective switching mechanism, an electrostatic actuation mechanism like that of Figure 14 could be employed if desired in switches of the general type shown in Figure 1. Other actuation mechanisms, such as electromagnetic mechanisms, can also be envisaged for switches of both the general types shown in Figures 1 and 9. In Figures 13 and 14 for example, pads 58a, 58b could be formed of a layer of magnetic material, and a coil could be provided on the substrate beneath each magnetic layer. Power can then be applied to a coil to attract the high-side magnetic layer and thus effect toggling of the switch. As a further alternative to the electrostatic mechanism of Figure 14, embodiments can be envisaged where the recess is fluid-filled and a nozzle or the like is provided in the substrate beneath each bridge section on either side of the mirror. An impulse could be applied to the nozzle on the low-side of the bridge to generate a pressure wave to push the low side up and thus toggle the switch. Further possibilities include piezoelectric or shape memory alloy actuation mechanisms as will be apparent to those skilled in the art. Moreover, in some embodiments the compressive stress characteristics and/or design geometry of the flexible bridge can be engineered to provide enhanced stability or give an asymmetric switching action, whereby the energy required to effect switching in one direction is greater than that required for the other direction. Many other changes can of course be made to the above embodiments without departing from the scope of the invention.

CLAIMS

1. A microsystem switch (1, 20, 25, 30, 33) comprising:  
a support (2) defining a recess (3);  
5 a flexible bridge (6) mounted on the support (2) and bridging the recess (3), the bridge (6) being shaped so as to hold selectively a concave stable state, in which the bridge bulges into the recess (3), and a convex stable state in which the bridge bulges out of the recess (3);  
an actuator (8, 9; 26, 27) for effecting flexing of the bridge (6) out of each of the stable states into the other of the stable states; and  
10 a switching element (7, 31, 34) mounted on the bridge (6) such that movement of the bridge between the stable states moves the switching element between an on position and an off position.
2. A switch as claimed in claim 1 wherein the bridge comprises a flexible membrane (6).  
15
3. A switch as claimed in claim 1 or claim 2 wherein the actuator comprises a pair of bimorph actuation layers (8, 9; 26, 27), each bimorph actuation layer extending over a respective portion of the bridge (6) to form therewith a bimorph structure such that differential expansion in the bimorph structure on activation of the bimorph actuation layer exerts a force  
20 causing flexing of the bridge out of one stable state into the other stable state, the arrangement being such that activation of one of said layers (8, 9; 26, 27) causes flexing of the bridge out of the convex stable state into the concave stable state, and activation of the other layer causes flexing of the bridge out of the concave stable state into the convex stable state.
- 25 4. A switch as claimed in claim 3 wherein each bimorph actuation layer comprises a heater (8, 9; 26, 27), having a thermal expansion coefficient different to that of said respective portion of the bridge (6), whereby heating of the heater produces said differential expansion.
5. A switch as claimed in claim 4 wherein the heaters (8, 9) are disposed on the same  
30 surface of the bridge (6) on opposite sides of the switching element (7, 31, 34), the thermal expansion coefficient of one heater being greater than that of said respective portion and the



thermal expansion coefficient of the other heater being less than that of said respective portion.

6. A switch (25) as claimed in claim 4 wherein the heaters (26, 27) are disposed on  
5 opposite surfaces of the bridge (6) and on opposite sides of the switching element.

7. A switch as claimed in any preceding claim wherein the bridge (6) is mounted on a substantially flat surface of the support (2) and the recess (3) is formed in said surface of the support.

10

8. A switch as claimed in any preceding claim wherein the bridge (6) has a substantially symmetrical curved profile in cross-section along the extent of the bridge across the recess (3), and wherein the switching element (7, 31, 34) is mounted substantially mid-way along said extent.

15

9. A switch as claimed in any preceding claim wherein the switching element (7, 31, 34) is mounted on the side of the bridge (6) remote from the recess (3).

10. A switch (20) as claimed in any preceding claim wherein the bridge (6) is formed with  
20 a spring structure (21) on each side of the switching element (7) in a direction along the extent of the bridge across the recess (3) to facilitate flexing of the bridge out of each stable state into the other stable state.

11. A switch (30, 33) as claimed in any one of claims 1 to 10 wherein the switching  
25 element comprises an electrical contact (31, 34).

12. A microsystem switch (40, 55) comprising:  
a support (41) defining a recess (42);  
an elongate torsion member (44) mounted on the support (41) and bridging the recess  
30 (42);  
a flexible bridge (43, 56) mounted on the support (41) and bridging the recess (42) in a direction substantially perpendicular to the torsion member (44), the bridge (43, 56) being

connected to the torsion member (44) at the cross-point thereof so that a first section of the bridge extends between the cross-point and one side of the recess (42) and a second section of the bridge extends between the cross-point and the opposite side of the recess (42), wherein the bridge (43, 56) is shaped so as to hold selectively a first stable state, in which the first  
5 section of the bridge bulges into the recess and the second section of the bridge bulges out of the recess, and a second stable state in which the first section of the bridge bulges out of the recess and the second section of the bridge bulges into the recess;

an actuator (46a, 46b; 58a, 58b) for effecting flexing of the bridge (43, 56) out of each of the stable states into the other of the stable states; and

10 a switching element (45) mounted at the cross-point of the bridge (43, 56) and torsion member (44);

wherein movement of the bridge (43, 56) between the stable states effects twisting of the torsion member (44) and rotation of the switching element (45) between an on position and an off position.

15

13. A switch as claimed in claim 12 wherein the cross-point is located substantially mid-way along the extent of each of the bridge (43, 56) and torsion member (44) across the recess (42).

20 14. A switch as claimed in claim 12 or claim 13 wherein the bridge comprises a flexible membrane (43, 56) and the torsion member comprises a torsion bar (44).

15. A switch as claimed in any one of claims 12 to 14 wherein the switching element (45) is mounted on the side of the cross-point remote from the recess (42).

25

16. A switch as claimed in any one of claims 12 to 15 wherein the switching element (45) comprises a substantially planar element mounted for rotation substantially in the plane thereof between the on and off positions.

30 17. A switch (40) as claimed in any one of claims 12 to 16 wherein the actuator comprises a pair of bimorph actuation layers (46a, 46b), each bimorph actuation layer extending over a said section of the bridge (43) to form therewith a bimorph structure such that differential

expansion in the bimorph structure on activation of the bimorph actuation layer (46a, 46b) exerts a force causing flexing of the bridge (43) out of one stable state into the other stable state, the arrangement being such that activation of one of said layers (46a, 46b) causes flexing of the bridge out of the first stable state into the second stable state, and activation of  
5 the other layer causes flexing of the bridge out of the second stable state into the first stable state.

18. A switch as claimed in claim 17 wherein each bimorph actuation layer comprises a heater (46a, 46b) having a thermal expansion coefficient different to that of said section,  
10 whereby heating of the heater produces said differential expansion.

19. A switch as claimed in claim 18 wherein the heaters (46a, 46b) are disposed on the same surface of the bridge (43), one on the first section of the bridge and the other on the second section of the bridge.

15

20. A switch (55) as claimed in any one of claims 12 to 16 wherein the support comprises a conductive substrate (59) and the actuator comprises a conductive layer (58a, 58b) on each of the first and second sections of the bridge (56), whereby application of a voltage between the substrate (59) and the conductive layer (58a, 58b) on a said section pulls that section  
20 towards the recess.

21. A switch (1, 20, 25, 40, 55) as claimed in any one of claims 1 to 10 and 12 to 20 wherein the switching element comprises an optical element (7, 45).

25 22. A switch as claimed in claim 21 wherein the optical element comprises a mirror.

23. Switching apparatus comprising an array of switches as claimed in any preceding claim.

30 24. An optical switching device comprising:  
a switch (1, 20, 25, 40, 55) as claimed in claim 21 or claim 22; and

a waveguide structure (10, 50) having an optical waveguide (11, 12, 51) and defining a cavity (13, 52) intersecting the waveguide;

wherein the switch (1, 20, 25, 40, 55) is disposed relative to the waveguide structure (10, 50) such that movement of the bridge (6, 43, 56) between said stable states moves the  
5 optical element (7, 45) in said cavity (13, 52) between the on position, in which the optical element intersects the optical path defined by the waveguide (11, 12, 51), and the off position in which the optical element does not intersect the optical path.

25. A switching device as claimed in claim 24 wherein:

10 the waveguide structure (10, 50) has a pair of crossed waveguides (11, 12, 51) and the cavity (13, 52) intersects both waveguides at the cross-point thereof;

the optical element (7, 45) comprises a mirror; and

the switch (1, 20, 25, 40, 55) is disposed relative to the waveguide structure (10, 50) such that, in the on position, the mirror is arranged to reflect light from one waveguide into  
15 the other.

26. Optical switching apparatus comprising an array of optical switching devices as claimed in claim 24 or claim 25.

20 27. Optical switching apparatus comprising an array of optical switching devices as claimed in claim 25 wherein:

the waveguide structures of the devices are provided by a waveguide array chip (50) and the switches of the devices are provided by a switch array chip (53);

the waveguides (51) are arranged in a grid on the waveguide array chip (50);

25 the mirror of each switch is mounted on the side of the bridge remote from the recess;  
and

the switch array chip (53) is disposed relative to the waveguide array chip (50) such that the mirror of each switch is located for movement between the on and off positions in the cavity (52) at the cross-point of a respective pair of waveguides (51).

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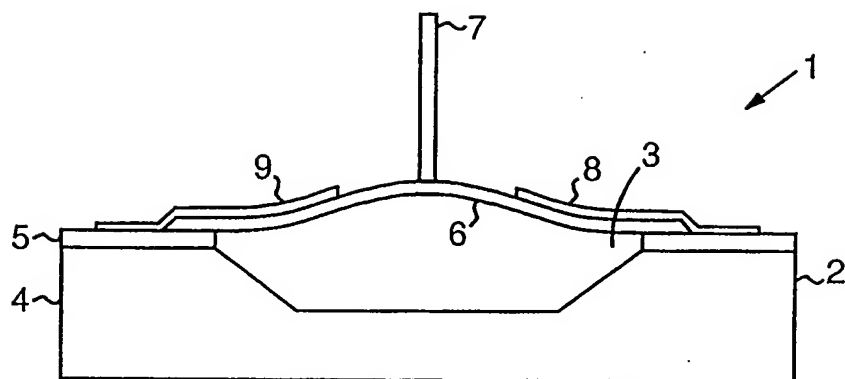


Figure 1

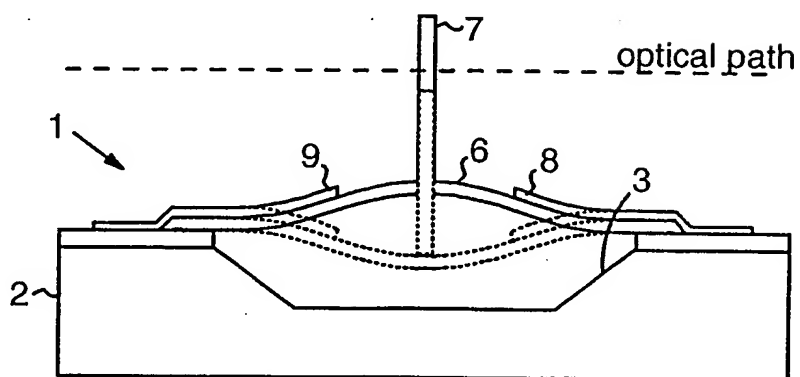


Figure 2

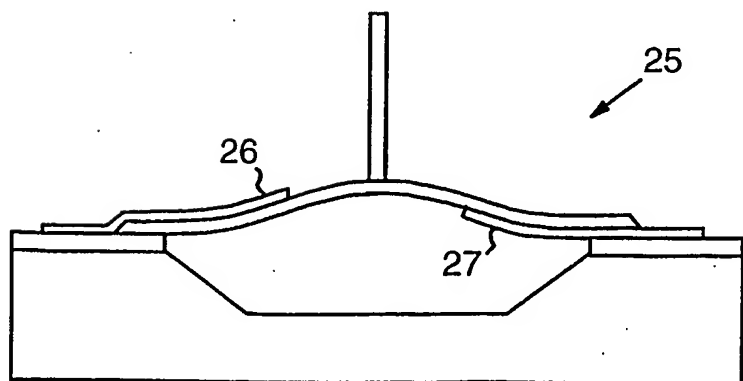


Figure 6

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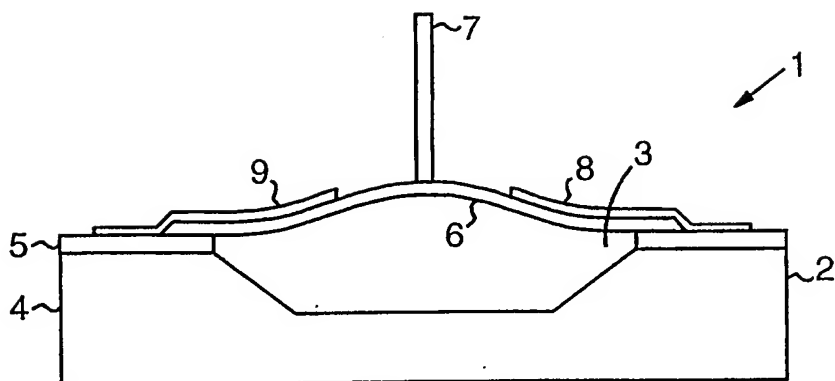


Figure 3a

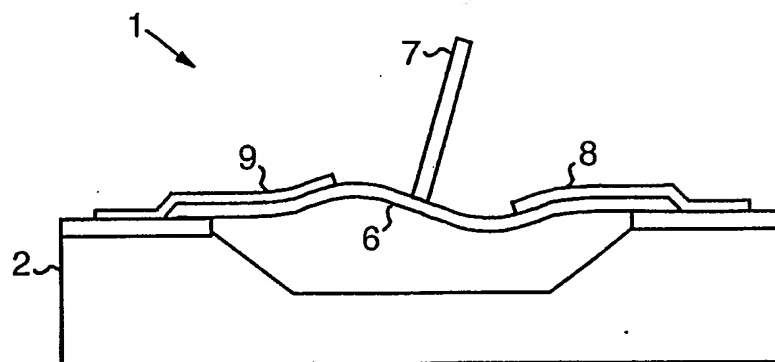


Figure 3b

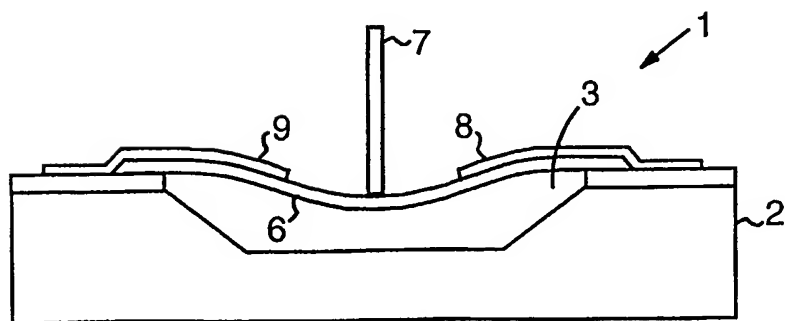


Figure 3c

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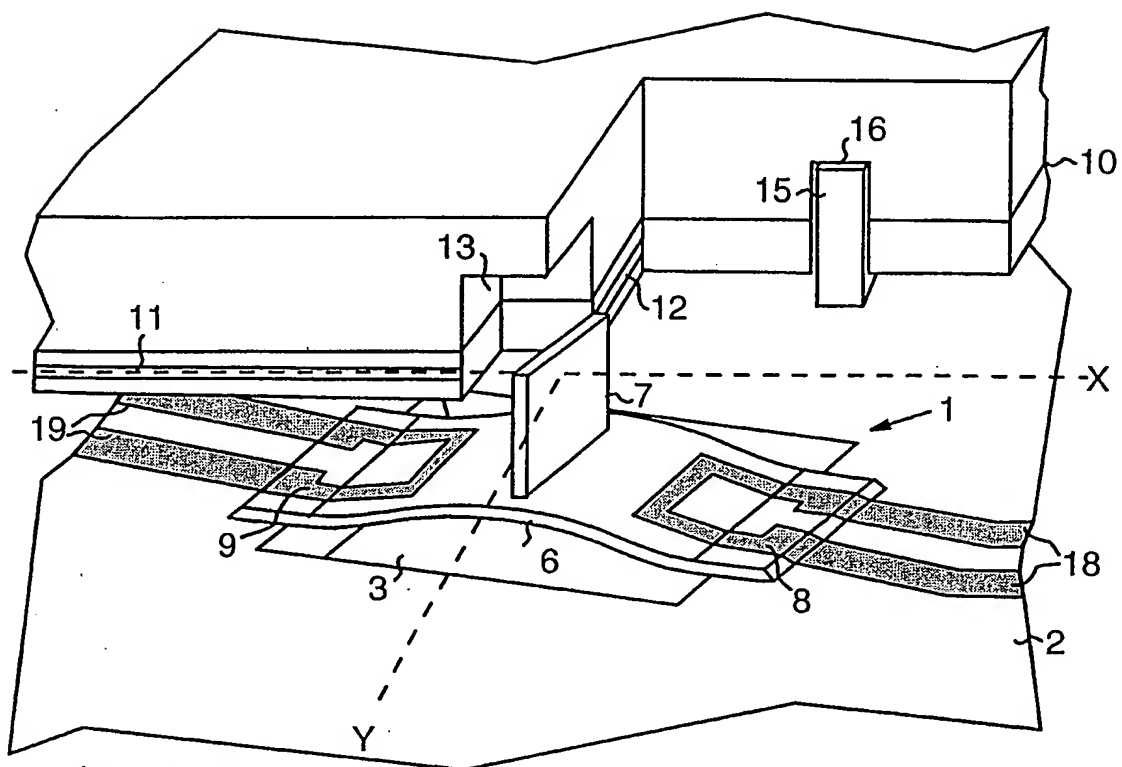


Figure 4

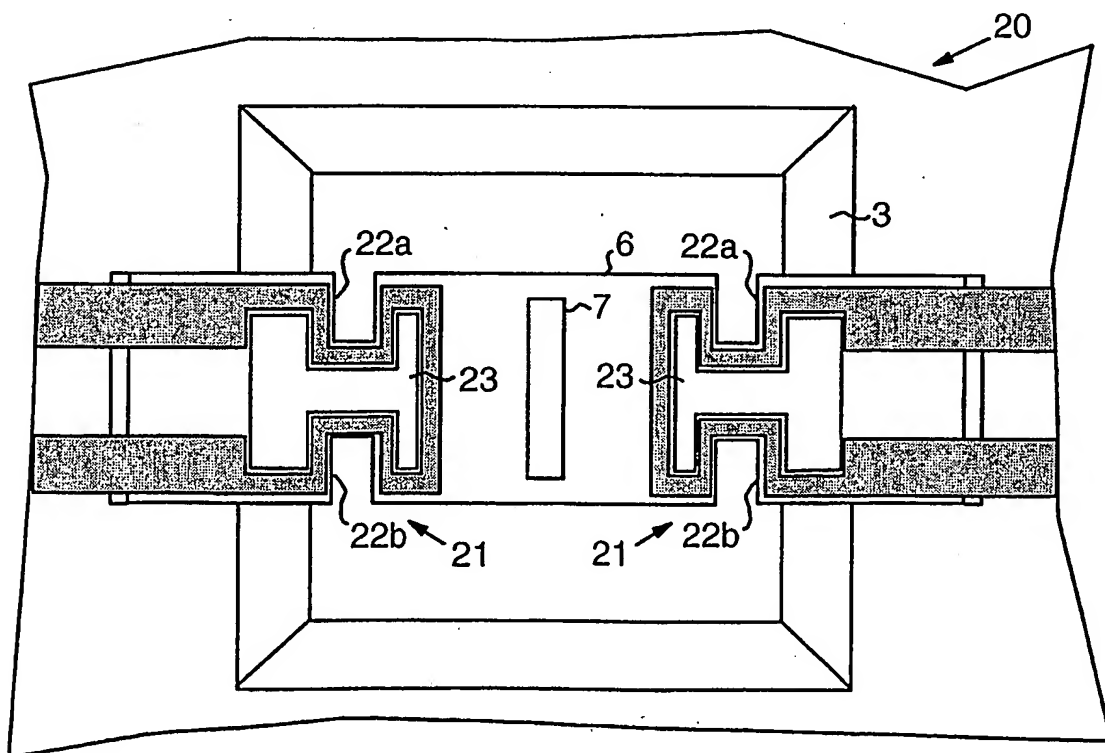


Figure 5

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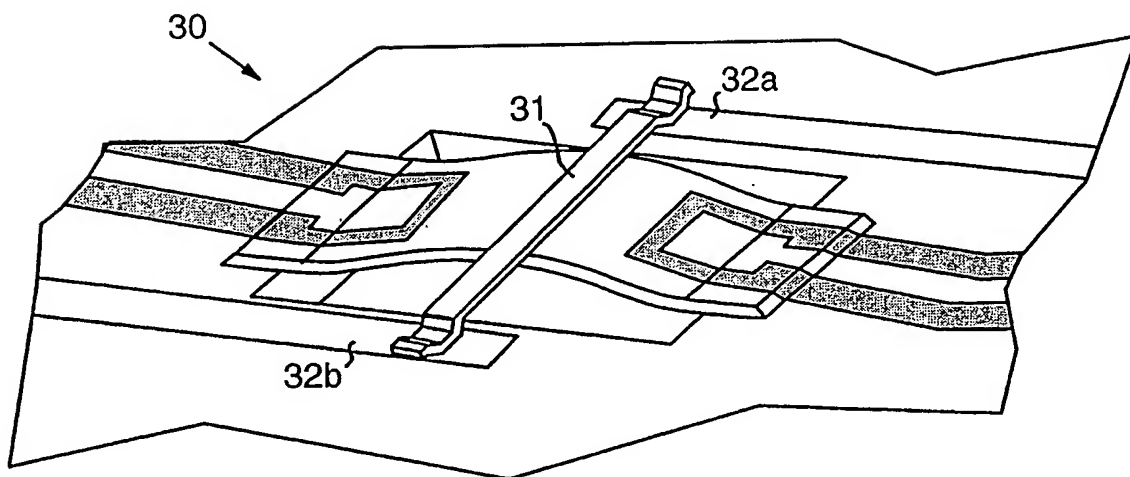


Figure 7

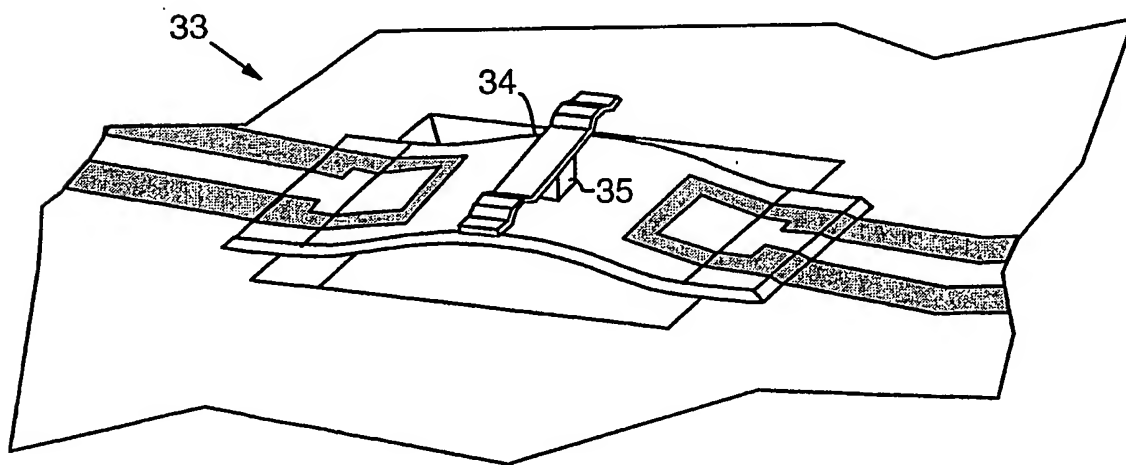
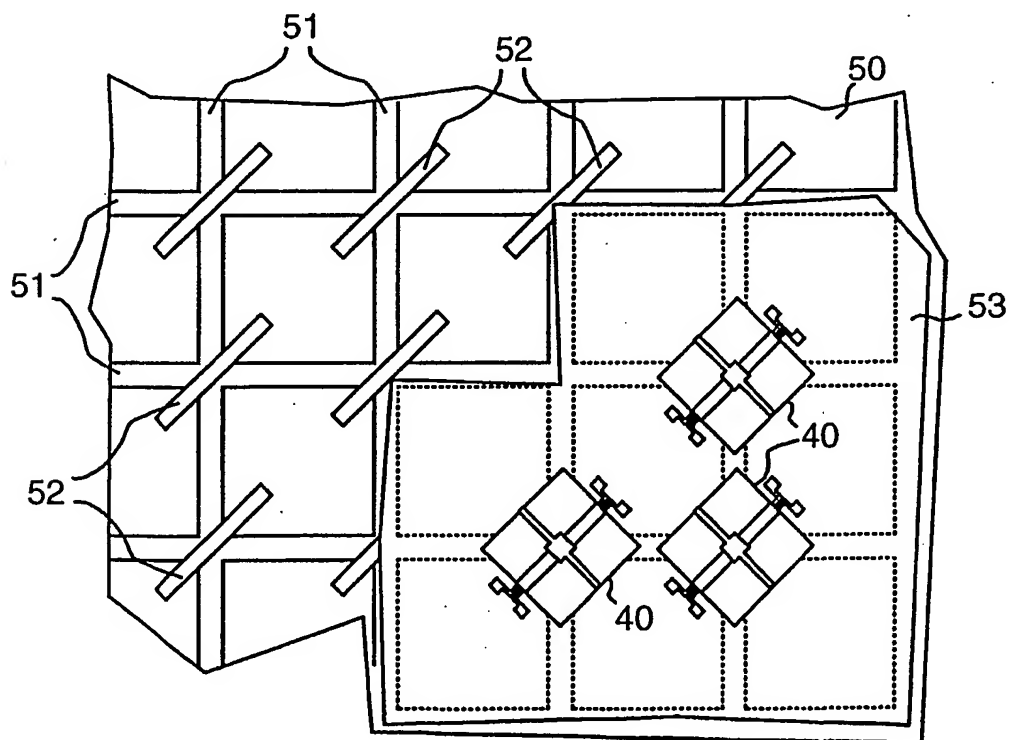
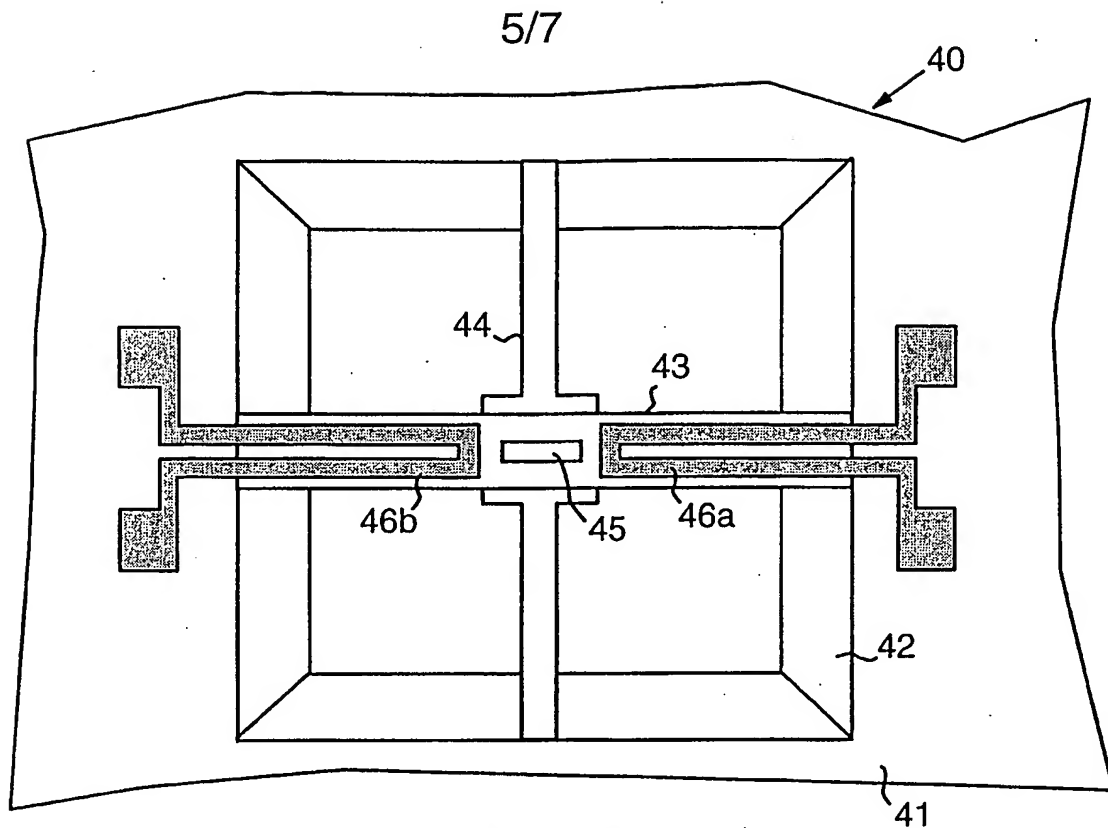


Figure 8





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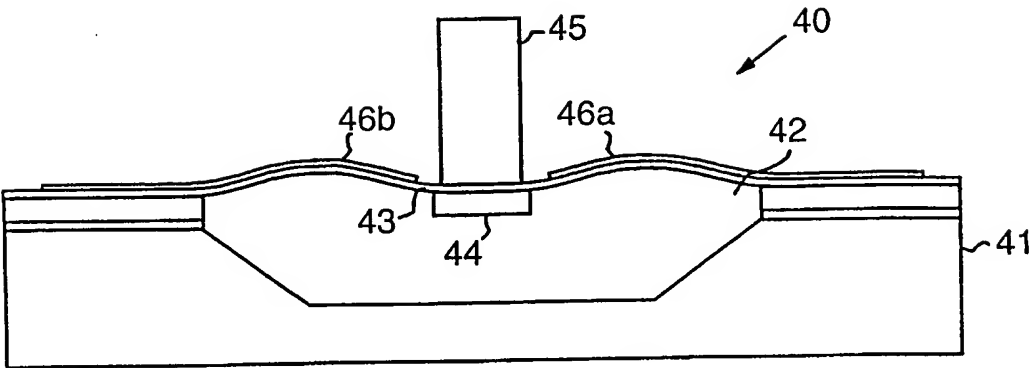


Figure 10

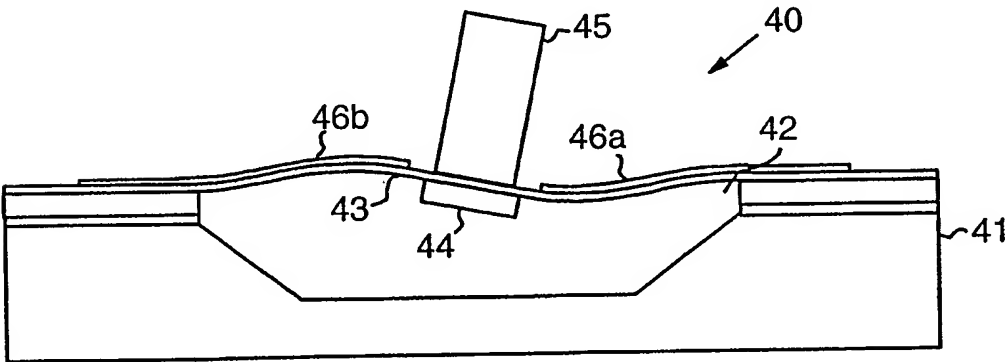


Figure 11a

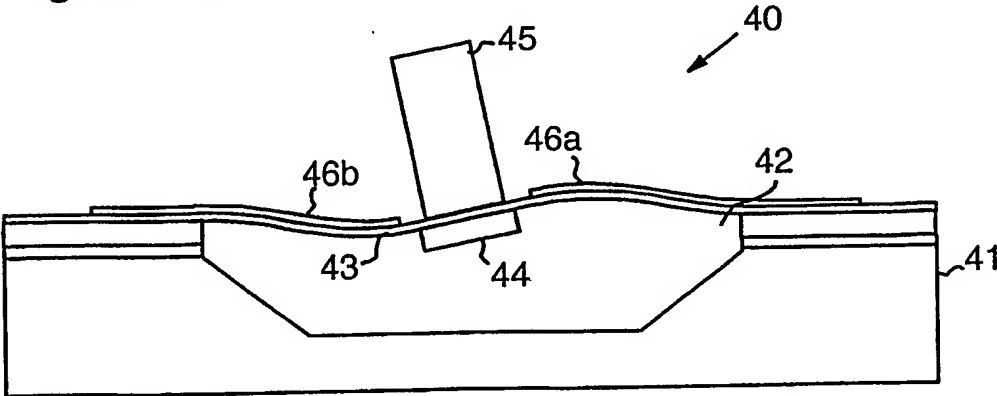


Figure 11b

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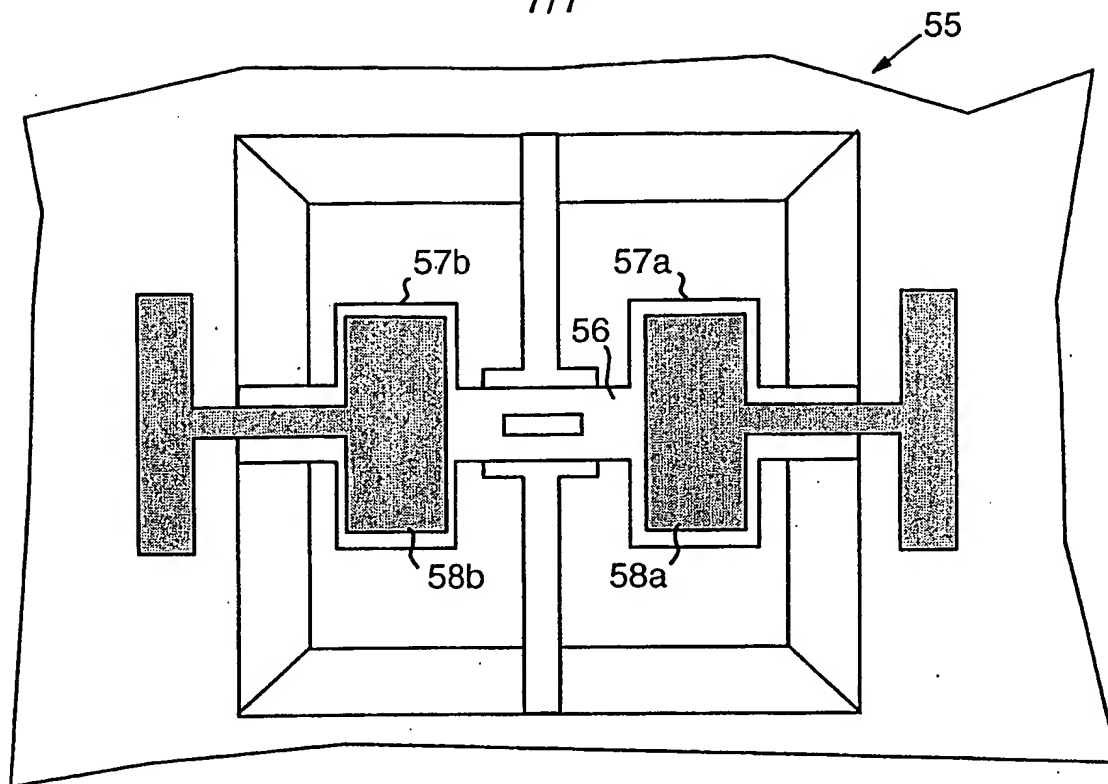


Figure 13

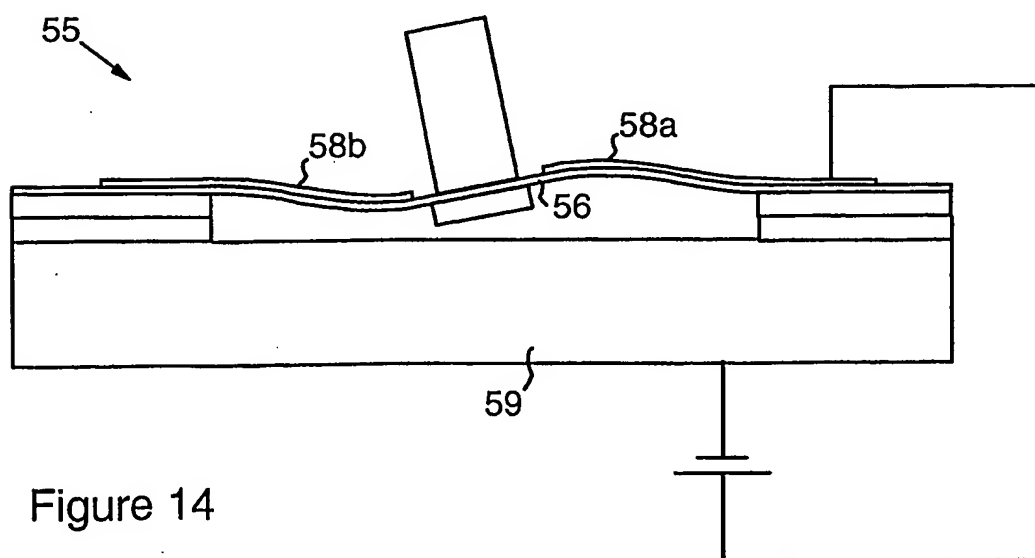


Figure 14

(19) World Intellectual Property  
Organization  
International Bureau



(43) International Publication Date  
20 February 2003 (20.02.2003)

PCT

(10) International Publication Number  
**WO 2003/014789 A3**

(51) International Patent Classification<sup>7</sup>: **G02B 6/35**,  
H01H 1/00, B81B 3/00

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(21) International Application Number:  
PCT/TB2002/002117

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(22) International Filing Date: 7 June 2002 (07.06.2002)

(81) Designated States (*national*): AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NO, NZ, OM, PH, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VN, YU, ZA, ZM, ZW.

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:  
01810658.3 5 July 2001 (05.07.2001) EP

(71) Applicant (*for all designated States except US*): INTERNATIONAL BUSINESS MACHINES CORPORATION [US/US]; New Orchard Road, Armonk, NY 10504 (US).

(84) Designated States (*regional*): ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

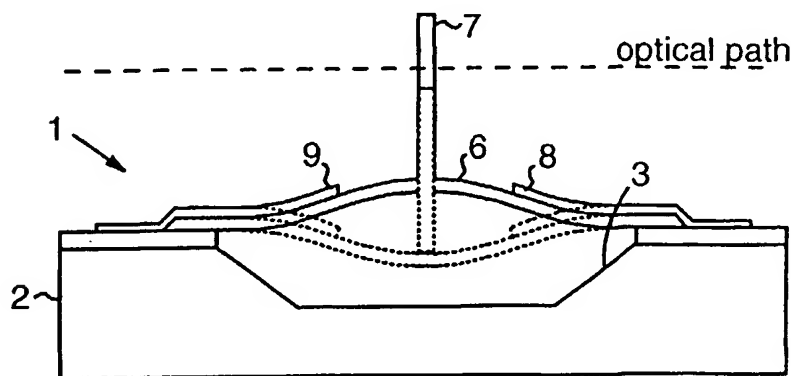
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Published:  
— with international search report

[Continued on next page]

(54) Title: MICROSYSTEM SWITCHES



(57) Abstract: A microsystem switch (1, 20, 25, 30, 33) has a support (2) defining a recess (3), and a flexible bridge (6) is mounted on the support (2) bridging the recess (3). The bridge (6) is shaped so as to hold selectively a concave support stable state, in which the bridge bulges out of the recess (3). The switch includes an actuator (8, 9; 26, 27) for effecting flexing of the bridge (6) between the stable states, and a switching element (7, 31, 34) is mounted on the bridge (6) such that movement of the bridge between the stable states moves the switching element between an on position and an off position. According to another design, a microsystem switch (40, 55) has a support (41) defining a recess (42), and an elongate torsion member (44) is mounted on the support (41) bridging the recess (42). A flexible bridge (43, 56) is mounted on the support (41) bridging the recess (42) in a direction substantially perpendicular to the torsion member (44). The bridge (43, 56) is connected to the torsion member (44) at the cross-point thereof so that a first section of the bridge extends between the cross-point and one side; of the recess, (42) and a second section of the bridge extends between the cross-point and the opposite side of the recess (42). The bridge (43, 56) is shaped so as to hold selectively a first stable state, in which the first section of the bridge bulges into the recess and the second section of the bridge bulges out of the recess, and a second stable state in which this configuration is reversed.



(88) Date of publication of the international search report:  
21 May 2004

*For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.*

## INTERNATIONAL SEARCH REPORT

PCT/IB 02/02117

## A. CLASSIFICATION OF SUBJECT MATTER

IPC 7 G02B6/35 H01H1/00 B81B3/00

According to International Patent Classification (IPC) or to both national classification and IPC

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC 7 H01H G02B B81B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the International search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, PAJ, INSPEC

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5 867 302 A (FLEMING JAMES G) 2 February 1999 (1999-02-02)  figures 1,3,4,7,8 column 3, line 17 -column 4, line 8 column 6, line 54 -column 10, line 55 column 12, line 6 -column 13, line 17 ---	1,2,8,9, 12-15, 20-23
A	FR 2 753 565 A (THOMSON CSF) 20 March 1998 (1998-03-20) page 5, line 19 - line 35 page 6, line 1 - line 8 page 7, line 24 - line 35 page 8, line 1 - line 35 figures 1-3,5,6 --- -/--	1-3,7,8, 11,23



Further documents are listed in the continuation of box C.



Patent family members are listed in annex.

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Date of the actual completion of the International search

18 December 2003

Date of mailing of the International search report

20.01.2004

Name and mailing address of the ISA

European Patent Office, P.B. 5818 Patentlaan 2  
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## INTERNATIONAL SEARCH REPORT

PCT/IB 02/02117

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT		
Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 6 229 640 B1 (ZHANG NAN) 8 May 2001 (2001-05-08) figures 1,2,4 column 3, line 28 -column 6, line 21 column 9, line 32 - line 55 ---	1,2,10, 21-27
A	FR 2 772 512 A (COMMISSARIAT ENERGIE ATOMIQUE) 18 June 1999 (1999-06-18) page 2, line 4 -page 4, line 19 page 4, line 32 -page 7, line 11 page 7, line 30 -page 8, line 34 page 17, line 14 -page 19, line 15 figures 1-5,9-12 ---	1-4,6
A	EP 0 880 040 A (LUCENT TECHNOLOGIES INC) 25 November 1998 (1998-11-25) figures 2,4,7 column 4, line 51 -column 11, line 5 ---	1,2,10, 21,22
A	L.DELLMANN ET.AL.: "4X4 MATRIX SWITCH BASED ON MEMS SWITCHES AND INTEGRATED WAVEGUIDES" TRANSDUCERS'01 EUROSensors XV, 11TH INTERNATIONAL CONFERENCE ON SOLID-STATE SENSORS AND ACTUATORS ,MUNICH,GERMANY,JUNE 10-14,2001, October 1906 (1906-10) - 14 June 2001 (2001-06-14), pages 1332-1335, XP002244596 MUNICH,GERMANY cited in the application the whole document ---	1,2,7,8, 10,21-27
A	US 5 148 506 A (MCDONALD T GUS) 15 September 1992 (1992-09-15) figures 1,2,4,7 column 1, line 41 - line 55 column 2, line 4 -column 5, line 8 ---	1,2,8, 12,21-26
A	EP 0 510 629 A (TEXAS INSTRUMENTS INC) 28 October 1992 (1992-10-28) column 1, line 12 - line 58 column 2, line 55 -column 6, line 31 -----	1,12,21, 24

# INTERNATIONAL SEARCH REPORT

PCT/IB 02/02117

## Box I Observations where certain claims were found unsearchable (Continuation of item 1 of first sheet)

This International Search Report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:  
because they relate to subject matter not required to be searched by this Authority, namely:
  
2. ☐ Claims Nos.:  
because they relate to parts of the International Application that do not comply with the prescribed requirements to such an extent that no meaningful International Search can be carried out, specifically:
  
3. ☐ Claims Nos.:  
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

## Box II Observations where unity of invention is lacking (Continuation of item 2 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

see additional sheet

1. ☒ As all required additional search fees were timely paid by the applicant, this International Search Report covers all searchable claims.
  
2. ☐ As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment of any additional fee.
  
3. ☐ As only some of the required additional search fees were timely paid by the applicant, this International Search Report covers only those claims for which fees were paid, specifically claims Nos.:
  
4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this International Search Report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

- ☐ The additional search fees were accompanied by the applicant's protest.
- ☒ No protest accompanied the payment of additional search fees.



## INTERNATIONAL SEARCH REPORT

International Application No. PCT/IB 02 02117

FURTHER INFORMATION CONTINUED FROM PCT/ISA/ 210

This International Searching Authority found multiple (groups of) inventions in this international application, as follows:

1. Claims: 1-11,21 till 27 only when dependent on claims 1-10

are directed to a microsystem switch comprising a support with a recess,flexible bridge on the support and bridging the recess and being shaped to hold two stable states(concave and convex) by bulging into and out of the recess,an actuator for flexing the bridge into the stable states and a switching element mounted on that bridge such that moving the bridge moves the switching element between on- and off-position.

2. Claims: 12-20,  
21 till 27 only when dependent on claims 12-20

are related to microsystem switch comprising a support with a recess,flexible bridge on the support and bridging the recess,an elongate tension member mounted on the support and bridging it in a direction perpendicular to the flexible bridge,bridge being connected to the torsion member and having two sections and holding two stable states by bulging the sections in each state into concave and convex shape,an actuator for flexing the bridge,switching element mounted at the cross-point of the bridge and torsion member such that moving the bridge effects twisting of the torsion member and rotation of the switching element between on- and off-position.

## INTERNATIONAL SEARCH REPORT

PCT/IB 02/02117

Patent document cited in search report		Publication date	Patent family member(s)	Publication date
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